RESPONSE OF THE ‘POLESIE’ RASPBERRY CULTIVAR TO FOLIAR APPLICATION OF CHITOSAN WITH DIFFERENT MOLECULAR WEIGHTS

Ireneusz Ochmian[1,a,*], Marcelina Krupa-Małkiewicz[2,b]

[1] – Department of Horticulture, West Pomeranian University of Technology Szczecin, Słowackiego 17 Str., 71-434 Szczecin, Poland
[a] – ORCID: 0000-0002-3606-1927
[2] – Department of Plant Genetics, Breeding and Biotechnology, West Pomeranian University of Technology Szczecin, Słowackiego 17 Str., 71-434 Szczecin, Poland
[b] – ORCID: 0000-0002-4333-9122
[*]corresponding author: iochmian@zut.edu.pl

Abstract
This study explored the effects of chitosan, a biodegradable and non-toxic natural polymer derived from chitin, on the yield and quality of raspberries. Various molecular weights (3.3–950 kDa) were assessed to determine the impact on raspberry plants and fruit development. These applications were made during key growth phases – the start of the vegetation period, during flowering and at the fruit-bearing stage – using a foliar method to ensure full coverage of both leaves and fruit without runoff. The results indicated that chitosan application influenced various parameters of fruit quality, including firmness, colour and antioxidant levels. Notably, chitosan with a molecular weight of 21 and 50 kDa significantly enhanced fruit yield and size compared with the control. Conversely, chitosan with a higher molecular weight (500 and 950 kDa) did not improve yield and appeared to induce stress in plants, although they did contribute to increased fruit firmness and potentially extended the shelf life due to their film-forming capabilities. The findings suggest that while chitosan can improve the yield and quality of raspberries, the effectiveness is highly dependent on its molecular weight. These results support the potential of chitosan as an alternative to traditional chemical treatments, promising a reduction in chemical inputs while sustaining or enhancing agricultural productivity and fruit quality.

Keywords: *antioxidant activity, colour, grey mould, firmness, fruit size, polyphenols*

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1. Introduction

Raspberries are grown throughout the world in temperate climates [1]. They are popular because of their taste and nutritional value. In Poland, raspberries are widely grown due to favourable climatic and soil conditions [2].

Raspberries have a unique flavour and many beneficial health-promoting properties. They are rich in antioxidants such as vitamin C, quercetin and anthocyanins [3]. These substances help fight free radicals in the body, which can contribute to protect against heart disease, cancer and cellular ageing [4]. The antioxidant components in raspberries help to reduce inflammation in the body, which may contribute to reduce the risk of many chronic diseases [5].

Raspberries are very tender fruit, susceptible to diseases, especially grey mould, powdery mildew, anthracnose and viral diseases [6–8]. Therefore, preventive measures should be applied to keep the plants in good condition: adequate pruning, irrigation, fertilisation and application of plant-protection products [9, 10].

Intensification of unfavourable factors drastically reduces yield and fruit quality. Many factors influence fruit quality, including climatic conditions such as drought, excessive moisture, frost, heat; diseases and pests; nutrient deficiencies; environmental pollution; and inappropriate cultivation techniques [11–13]. Harvesting the fruit at the right time of ripening ensures the optimal aroma, size colour and firmness. Firmness or mechanical resistance are considered good indicators of raspberry quality [14]. Fruit firmness decreases gradually with ripening. It indicates the suitability of the fruit for harvesting, transport, consumption or freezing as well as the susceptibility of the fruit to fungal diseases [15]. Intensive chemical protection must be applied to produce healthy raspberries. However, the widespread use of chemical plant protection products is one of the causes of environmental degradation.

In recent years, measures have been taken to reduce the over-chemicalisation of agricultural production. Alternative methods are being sought to protect plants from disease. One such natural substance that is being used in agricultural production is chitosan [β(1→4)-D-glucosamine and *N*-acetyl-D-glucosamine]. It is a non-toxic and biodegradable compound of natural origin, obtained by deacetylation of chitin [16, 17]. Chitin is a key structural component in the exoskeletons of crustaceans such as crabs, shrimp and lobsters; the cell walls of fungi; and the exoskeletons of insects [18]. When applied to plants, chitosan reduces transpiration and induces a number of metabolic changes, increasing their resistance to infection by pathogens [19]. As a natural macromolecular polysaccharide, chitosan is a partially deacetylated chitin product with different molecular weights and degrees of deacetylation [20, 21].

The effectiveness of solutions prepared based on chitosan varies widely and depends on its molecular weight. High-molecular-weight chitosan (360 kDa) delays fruit ripening, but results in higher post-harvest quality compared with low-molecular-weight chitosan (40 kDa) [22]. However, low-molecular-weight chitosan, exemplified by oligomers of chitosan lactate, shows better solubility in water [23]. Therefore, such formulations should be tested for suitability in raspberry cultivation. The present study aimed to investigate the effect of foliar-applied chitosan of different molecular weights on raspberry yield and quality.

2. Materials and Methods

2.1. Characteristics of the Research Area and Plant Material

The experiment was conducted at the Horticulture Department of the West Pomeranian University of Technology, Szczecin, Poland. The Polish raspberry cultivar Polesie was studied. These raspberries are consumed as is and are also frozen and processed into products such as juices. These plants bear raspberries on 1-year-old shoots, a process called repeat fruiting. The cultivar is recommended for ecological cultivation.

Raspberries were harvested successively as they ripened from the production plantation during the harvest. The plants received limited chemical protection according to the accepted rules for organic plantations.

The experiment was established on a precipitous-gley podzolic soil developed from till with a mechanical composition of light clay (26–35 mm fraction < 0.02 mm) [24] under the climatic conditions of north-western Poland [25].

During the experiment, the plants were treated throughout the growing season according to the established rules. The soil was watered using a permanently mounted T-Tape drip line with an emitter capacity of 1 l/h (5 l of water/h over a 1 mb section of the system). The doses and intensity of water emitted were modified according to the degree of soil moisture, determined by contact soil tensiometers.

The orchard used agricultural soil with a natural profile developed from silt-loam with a pH of 6.5. The soil in which the shrubs grew had a high content of phosphorus (P, 88 mg/kg), potassium (K, 145 mg/kg) and magnesium (Mg, 66 mg/kg). Annually, from the start of vegetation (March/April), 90 kg of nitrogen (N) was applied as three equal doses.

2.2. Weather Conditions During the Experiment

Several significant trends and changes can be observed when analysing the data on the temperature and rainfall in Szczecin during the vegetation period from April to October in the years 2020–2022 compared with the long-term period (1951–2012) (Table 1). The temperatures in 2020–2022 were mostly higher than the long-term average, indicating a warming trend. For example, in July and August 2021 and 2022, the temperatures were significantly higher than the long-term average temperatures. The average temperature in 2020–2022 (14.4–14.6°C) was higher than the long-term average (13.7°C). Rainfall in 2020–2022 was generally lower than the long-term average for this period (390.6 mm). For example, the total rainfall in 2020 was 258.1 mm, which is significantly below the norm. There were significant fluctuations in rainfall,especially in July 2021, where rainfall reached 123 mm compared with the long-term average of 69.6 mm. Meanwhile, no rainfall was recorded in June. The higher temperatures and lower rainfall compared with the long-term averages are consistent with general trends of climate change. These changes may pose challenges for agriculture in the Szczecin region and require adjustments in agricultural practices to manage water resources effectively and to maintain healthy conditions for crops.

Table 1. The temperature and rainfall in the period from April to October (vegetation season) in 2020–2022 compared with the long-term period (1951–2012) in Szczecin, Poland.

	Month							
	IV	V	VI	VII	VIII	IX	X	Mean
Year	Average temperature (°C)							
2020	8.9	11.1	17.7	17.4	20.3	14.6	10.5	14.4
2021	5.9	11.6	19.3	20.3	16.7	15.1	10.1	14.1
2022	7.2	13.3	18.1	18.4	20.6	12.9	11.6	14.6
1951–2012	8.0	13.0	16.4	18.2	17.6	13.8	9.2	13.7
Rainfall (mm)								total
2020	20.1	34.0	26.6	21.3	40.0	72.3	43.8	258.1
2021	4.6	25.1	0.0	123	37.4	17.1	24.7	231.9
2022	19.9	25.2	27.6	67.5	23.4	39.0	22.2	224.8
1951–2012	39.7	62.9	48.2	69.6	74.2	58.7	37.3	**390.6**

2.3. Edible Coating Preparation and Application of Treatments

Samples with varying molar masses were prepared by controlled radical degradation of chitosan with a molecular mass > 1200 kDa (chitosan HMW, Aldrich, USA) in the Department of Packaging and Biopolymers of the West Pomeranian University of Technology, Szczecin, Poland. Samples were obtained via continuous addition of hydrogen peroxide (0.8−6.4 mM/g of polysaccharide) to 2.5% chitosan solution with pH 3.5–4.0 at 80°C. After degradation, all samples, as chloride salts, had similar polydispersity and a high degree of deacetylation (> 95%). The molar mass of each sample was determined using the high-performance liquid chromatography (HPLC)/gel permeation chromatography (GPC) method (HPLC SmartLine system with an isocratic pump 1000 equipped with an RI Detector 2300; Knauer, Germany).

Raspberry plants were treated with chitosan with the following molecular weights: 3,333 Da (3.3k), 5,000 Da (5k), 12,000 Da (12k), 21,000 Da (21k), 50,000 Da (50k), 125,000 Da (125k), 500,000 Da (500k) and 950,000 Da (950k). Chitosan was dissolved in 300 g of distilled water, and the solution was titrated to a pH of 7.7 by adding 1 M sodium hydroxide (NaOH). Then, the volume was adjusted to 500 g with distilled water, and 500 g of 0.2 M acetic acid was added.

Annually, the plants were sprayed with a 0.2% chitosan solution (0.2 l per metre of row), prepared from the aforementioned chitosan with different molecular weights, ensuring full wetting (without allowing the solution to drip from the plants) of the leaves and, later in the season, both leaves and fruit. The spraying was carried out in the morning using a battery-operated backpack sprayer. The application was planned at the start of the vegetation period, three times during the flowering phase, and three times during the fruit-bearing stage. Conversely, the control plants were sprayed with distilled water. Throughout this study, no additional chemical protections were administered to the plants.

In the experiment, three plots were designated for each treatment/chitosan. Raspberry plants were planted in 2015 with a spacing of 3 × 0.3 m. In the subsequent years, the raspberry rows became denser. Each year, the excess of new plants was reduced: in the spring, they were removed using a rototiller, and during the growing season, plants that grow in the row spacings were mowed. Each plot consisted of a raspberry plant row section 1 m in length and approximately 30 cm in width. Six hundred litres of solution were applied per hectare, which equals 0.2 l of solution per metre of raspberries.

2.4. General Fruit Parameters

Raspberries were harvested when fully ripe, based on the assessment of their colour, and successively throughout the vegetation season. The yield, weight of 100 raspberries, firmness and colour were measured immediately after harvest. Other analyses were performed on frozen raspberries, after the harvest season had ended. Annually, three composite samples were prepared from individual harvest dates (50 g from each harvest). Raspberries from the first and last harvests were not used for the analyses.

Annual measurements were taken to determine the yield and fruit mass using a RADWAG WPX 4500 scale (RADWAG, Poland, accuracy of ± 0.01 g). The soluble solid content was assessed using a PAL-1 electronic refractometer (Atago, Japan). The acidity level was determined by titrating the water extract with 0.1 N NaOH until reaching a pH of 8.1, using an CX-732 digital multimeter (Elmetron, Poland), as per the PN-2001 standard. The levels of L-ascorbic acid, nitrates and nitrites were analysed using a RQflex 10 reflectometer (Merck, Germany), as documented by Ochmian et al. [25].

2.5. Colour

The colour parameters and indices were determined by averaging 50 measurements using a CM-700d spectrophotometer (Konica Minolta, Japan), as detailed by Ochmian et al. [25], within the CIELab* colour space.

2.6. Firmness

The firmness and puncture resistance of the skin were assessed using a FirmTech2 device (BioWorks, USA) on 100 raspberries chosen at random from three replicates, as described by Ochmian et al. [26]. The results are expressed as the gram force required to cause a 1-mm deformation of the fruit surface.

2.7. Antioxidant Activity

Samples (1 g) were mixed with methanol (80%; 10 ml) and then with hydrochloric acid (1%). This process was performed twice by incubating the above slurry for 20 min under sonication. Next, the slurry was centrifuged at 19,000 g for 10 min, and the supernatant was filtered through a hydrophilic poly(tetrafluoroethylene) (PTFE) 0.20 µm membrane (Merck, Germany) and used for analysis [27].

The 2,2'-azobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical scavenging assay was conducted using the method described by Arnao et al. [28]. The 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging assay was performed in accordance with the protocol established by Brand-Williams et al. [29]. The ferric reducing antioxidant power (FRAP) assay followed the procedure outlined by Benzie and Strain [30].

For the quantification of total polyphenols, supernatants were analysed using the Folin–Ciocalteu method, with absorbance measured at 675 nm, as indicated by Singleton et al. [31].

2.8. Statistical Analysis

Statistical analyses were conducted using Statistica 12.5 (StatSoft Polska, Poland). The data were submitted to one-way analysis of variance (ANOVA) followed by Tukey's least significant difference test. A p value < 0.05 was considered to indicate a statistically significant difference.

3. Results and Discussion

The optimal molecular weight of chitosan appears to vary depending on the developmental stage of the plants. In the early fruit harvesting period (July), the yield was similar to that of the control plants, except for plants sprayed with 500k or 950k chitosan (Figure 1). Moreover, 500k and 950k chitosan did not favour yield, suggesting the existence of a threshold beyond which the efficiency of chitosan may decrease. The yields for 500k and 950k chitosan dropped to 12.1 t/ha and 12.4 t/ha, respectively, compared with 13.3 t/ha for the control (Table 2). The raspberries sprayed with 500k and 950k chitosan were also the smallest. The yield of plants sprayed with 12k chitosan was also low (12.5 t/ha). The 21k and 50k chitosan treatments led to the highest yields: 14.6 and 15 t/ha, respectively. In addition, 21k chitosan had a very positive effect on the size of raspberries, with an average weight of 100 raspberries of 451 g, much higher than the 315 g for the control. A reduction in yield is natural at the end of the growing season. However, treatment with 500k and 950k chitosan sustained higher yields in the first and second decades of October. This confirms the results of previous studies, which also showed that chitosan increased raspberry yield and size [14]. Chitosan can increase fruit mass through various mechanisms that improve health, enhance nutrient uptake, reduce abiotic stress or delay aging and ripening, allowing the fruit to remain on the plant longer and to continue to increase in mass before harvesting [32–34]. During spraying, a coating is formed on the fruit, which may slightly increase their mass by adding an additional layer of material on the surface. However, this coating can also reduce water loss, further affecting the maintenance of fruit mass [35].

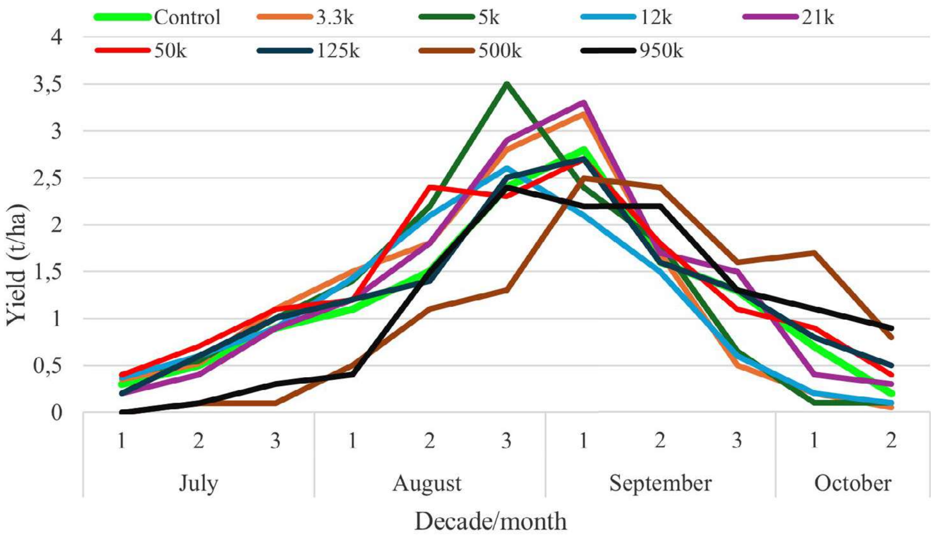

Figure 1. Yield distribution of Polesie raspberries at harvest depending on the chitosan applied. The graph shows the decadal average for 2020–2022.

Table 2. The yield, firmness, mean weight of 100 raspberries and antioxidant properties.

	Chitosan molecular weight								
	Control	**3.3k**	**5k**	**12k**	**21k**	**50k**	**125k**	**500k**	**950k**
Total yield [t/ha]	13.3^{b}	13.7^{bc}	14.1^{cd}	12.5^{a}	14.6^{de}	15.0^{e}	13.8^{c}	12.1^{a}	12.4^{a}
Mean weight of 100 raspberries [g]	315^{bc}	422^{f}	434^{fg}	378^{e}	451^{g}	336^{cd}	349^{d}	299^{b}	270^{a}
Firmness of raspberries with a floral base [G mm^{-1}]	152^{ab}	137^{a}	146^{ab}	158^{bc}	134^{a}	160^{bc}	153^{ab}	175^{cd}	189^{d}
Soluble solids [%]	11.3^{bc}	12.2^{f}	11.9^{ef}	11.5^{cd}	11.8^{de}	10.6^{ce}	11.0^{b}	11.8^{de}	11.6^{ce}
Titratable acidity [g 100 g^{-1}]	1.88^{c}	1.55^{a}	1.80^{bc}	1.94^{cd}	1.79^{bc}	2.13^{d}	1.85^{c}	1.61^{ab}	1.56^{a}
N–NO$_3$ [mg 1000 g^{-1}]	72^{ab}	118^{e}	102^{d}	91^{c}	75^{b}	64^{a}	88^{c}	97^{cd}	112^{e}
N–NO$_2$ [mg 1000 g^{-1}]	0.09^{ab}	0.11^{bc}	0.12^{c}	0.11^{bc}	0.15^{d}	0.10^{ab}	0.10^{ab}	0.08^{a}	0.10^{ab}
L–ascorbic acid [mg 1000 g^{-1}]	58^{bd}	52^{ac}	64de	70^{e}	55^{ad}	49^{ab}	60^{cd}	51^{ac}	46^{a}
Polyphenols [mg/100 g]	113^{bc}	122^{c}	105^{bc}	125^{c}	99^{ab}	82^{a}	94^{ab}	171^{d}	164^{d}
DPPH [mmol TE/100 g]	47^{ab}	42^{bc}	47^{ab}	45^{b}	51^{ab}	55^{a}	49^{ab}	35^{cd}	32^{d}
ABTS+ [mmol TE/100 g]	15^{bc}	17^{av}	19^{ab}	20^{a}	14^{c}	15^{bc}	19^{ab}	16^{ac}	16^{ac}
FRAP [mmol/100 g]	65^{bd}	61^{cd}	72^{a}	70^{ab}	66^{bc}	73^{a}	60de	55^{e}	48^{f}
% of fruit infected by grey mould (*Botrytis cinerea*) after a 3-day shelf life	37^{a}	32^{ab}	30^{b}	15^{d}	28^{b}	22^{c}	11^{d}	4^{e}	5^{e}

Note. In each row, means with the same superscript letter do not differ significantly according to Tukey's test ($p > 0.05$). Abbreviations: ABTS, 2,2'-azobis(3-ethylbenzothiazoline-6-sulfonic acid); DPPH, 1,1-diphenyl-2-picrylhydrazyl FRAP, ferric reducing antioxidant power; N-NO$_2$, nitrite nitrogen; N-NO$_3$, nitrate nitrogen; TE, Trolox equivalents

The data revealed that raspberry firmness varied depending on the molecular weight of chitosan used. Firmness is an important parameter that affects quality, shelf life and consumer preferences for fruits. In this study, 500k and 950k chitosan increased raspberry firmness. This ability could be useful in agricultural and processing practices to improve fruit quality. However, the question remains whether the raspberries were firmer due to the application of 500k or 950 k chitosan or due to the negative impact of the treatment on raspberry size. Zhang et al. [36] showed that a coating on fruit made of low-molecular-weight chitosan increased fruit firmness.

Raspberries treated with 3.3k chitosan showed the highest content of soluble solids (12.2%). These raspberries also had the lowest titratable acidity (1.55 g), which gives consumers the impression that they are sweeter. This suggests that chitosan with a lower molecular weight may favour the accumulation of sugars, despite the fact that the raspberries were large and the yield was higher compared with the control. Plants sprayed with 50k chitosan had the lowest amount of sugars and, at the same time, the highest acidity. Meng et al. [37] and Zhang et al. [36] showed that the use of chitosan increased the extract content and slightly reduced the acidity of fruit.

In Poland, there are no established standards that define the level of nitrates and nitrites in fruits. Raspberries accumulated very small amounts of harmful nitrates (maximum 118 mg/1000 g) and nitrites (maximum 0.12 mg/1000 g), regardless of the chitosan used. According to the current regulations, they can be considered safe for consumers. The limits for the nitrate content are defined in European Union (EU) regulations only for green leafy vegetables. For example, fresh lettuce can contain up to 5000 mg nitrates/1000 g. Meanwhile, processed food intended for infants and small children should not exceed 200 mg nitrates/1000 g and 0.07 mg nitrites per kilogram of body weight [38].

Polyphenols are important for the antioxidant properties of fruits. The use of chitosan impacted the polyphenol content and antioxidant activity of raspberries, measured by the DPPH and ABTS radical scavenging assays and the FRAP assay, which measures the antioxidant capacity through the ability to reduce iron. Lower values indicate a better ability to neutralise free radicals. Each of these indicators provides information about the potential health benefits of raspberries, especially in the context of preventing diseases related to oxidative processes. The raspberries treated with 500k and 950k chitosan had the highest polyphenol content, 171 mg/100 g and 164 mg/100 g, respectively. This suggests that higher molecular weights of chitosan may better support the synthesis of polyphenols in raspberries, but also may cause stress in plants. Polyphenols can be synthesised by plants in response to stress. Furthermore, raspberries treated with 500k and 950k chitosan were smaller, and other studies have shown that smaller fruits contain more polyphenols [39].

Raspberries treated with 3.3k and 12k chitosan also showed an elevated polyphenol content compared with the control, although this effect was more moderate. The highest DPPH radical scavenging and FRAP activity correlated with a high polyphenol content. In raspberries collected in Japan, the antioxidant activity measured by FRAP was 18.0 mmol Trolox equivalents (TE)/100 g [40]. The ABTS scavenging assay did not show an effect of the applied chitosan on the antioxidant capacity of raspberries. High- and medium-molecular-weight chitosan had an antioxidant capacity of the fruits similar to that of the control, while low-molecular-weight chitosan even weakened this effect.

Vitamin C, also known as ascorbic acid, is one of the most recognisable and effective antioxidants available in the human diet [41]. The antioxidant capacity of vitamin C is related to its ability to neutralise free radicals and other reactive oxygen species, which can cause cell damage, contribute to the development of cardiovascular diseases and certain types of cancers and accelerate ageing. However, the results did not show a correlation between the content of this compound and the antioxidant capacity. Raspberries sprayed with 950k chitosan had the lowest L-ascorbic acid content. This suggests that the high antioxidant capacity is influenced by polyphenols and not by the content of L-ascorbic acid. On the contrary, Zhang et al. [36] demonstrated that low-molecular-weight chitosan increased the L-ascorbic acid content.

As a natural polysaccharide, chitosan exhibits a variety of properties that can be particularly useful in the protection of plants and fruits against pests and diseases [36, 42]. Chitosan can induce so-called systemic acquired resistance in plants, which strengthens their natural defence mechanisms. Chitosan also demonstrates direct antifungal action: it can damage the cell walls of fungi by binding to their polymers, leading to disturbances in their growth and development [43]. Additionally, alteration of the environmental pH by chitosan can adversely affect the survival of fungi. When applied to the surface of fruits, chitosan forms a thin, transparent and breathable coating, which can physically limit the access of pathogens to plant tissue, acting as an additional protective barrier [36]. It is difficult to determine which method enhanced the resistance of raspberries against grey mould. Perhaps several defence systems operated simultaneously. All the applied sprays reduced the degree of raspberry infestation compared with the control group. Raspberries treated with 500k and 950k chitosan were the best protected, with only 4%–5% of the fruit being affected. Chitosan 125k was also effective: 11% of the fruit was affected. Badawy and Rabea [44] also found that the effectiveness of chitosan was dependent on its molecular weight.

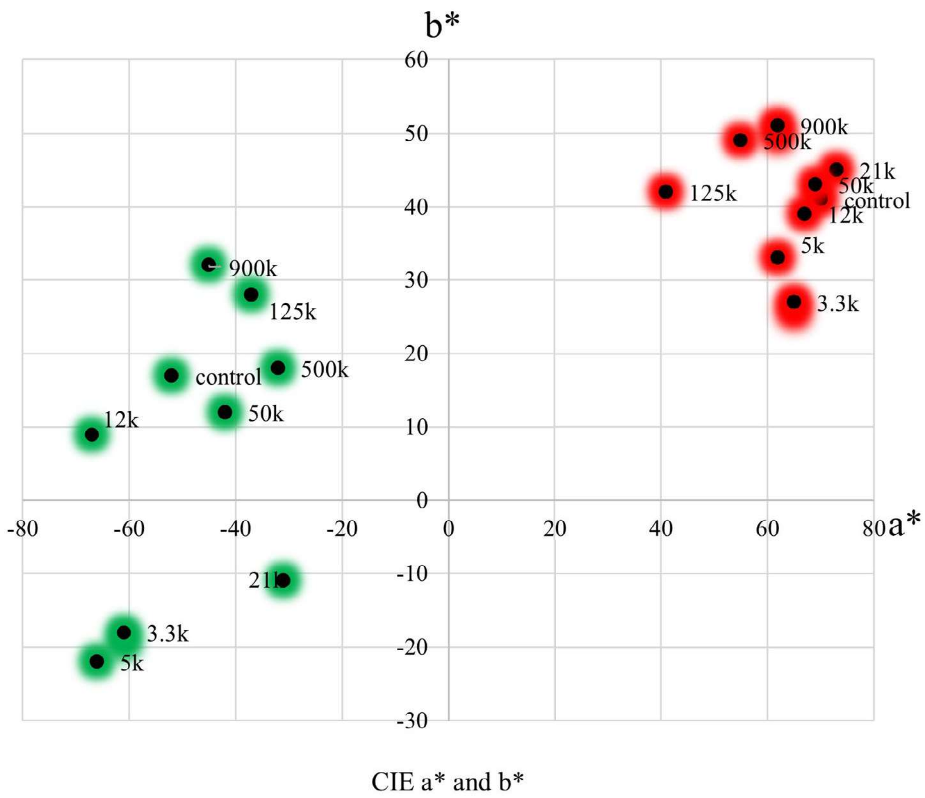

Figure 2. The effects of chitosan on the colour of the leaves and raspberries for the Polesie cultivar. The green markers indicate the values for leaves, while the red markers indicate the values for raspberries.

Chitosan of various molecular weights had a significant impact on the colour of the leaves and raspberries. Treatment with 3.3k chitosan increased the colour intensity of the leaves and raspberries, with a more pronounced effect on the leaves (Figure 2). The b* parameter took a negative value, meaning that the leaves had an intense green-blue colour, reminiscent of the effect of over-fertilisation with nitrogen. As the chitosan molecular weight increased, this effect was weaker. Treatment with 950k chitosan resulted in the least intensely coloured leaves and raspberries. The opposite effect was observed in strawberries: chitosan with the highest molecular weight produced strawberries with a better colour [45]. Hence, the reaction of different plant species varies, a phenomenon that requires additional research.

4. Conclusions

This study on the impact of chitosan with various molecular weights on the development, quality and health of raspberries highlights the complex interactions between this biopolymer and plants. The results suggest that the optimal molecular weight of chitosan may vary depending on the application goal and the developmental phase of the plants. Treatment with 21k and 50k chitosan resulted in the highest raspberry yield. Moreover, 21k chitosan also impacted raspberry size positively. However, 500k and 950k chitosan reduced the yield compared to the control. On the other hand, chitosan with higher molecular weights favourably influenced the firmness of the raspberries, which is significant from a quality perspective. The raspberries treated with 3.3k chitosan had the highest content of soluble substances and the lowest acidity, which could contribute to the perception of greater sweetness. Raspberries sprayed with chitosan, regardless of its molecular weight, accumulated small amounts of harmful nitrates and nitrites, although they stayed the within the established safe limits for consumers. Treatment with 500k and 950k chitosan favoured the accumulation of polyphenols, which may indicate their better properties in supporting the antioxidant capabilities of the fruit, although this could also be related to plant stress. Chitosan, especially 500k and 950k, demonstrated protective action against grey mould. This suggests that chitosan may induce defence mechanisms in plants or create a physical protective barrier on the surface of the fruits. This type of chitosan tends to form stronger and more durable barriers, enhancing plant defence mechanisms against pathogens. In summary, this research indicates the potential benefits from the use of chitosan in agriculture, particularly in increasing yields, improving fruit quality and protecting against diseases. However, selecting the appropriate molecular weight of chitosan is crucial to realising these benefits, an issue that requires further research and refinement.

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